

FCC based ep and μp colliders

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Abstract

Construction of future electron-positron colliders (or dedicated electron linac) and muon colliders close to Future Circular Collider will give opportunity to utilize highest energy proton and nucleus beams for lepton-hadron and photon-hadron collisions. In this paper we estimate main parameters of the FCC based ep and μp colliders.

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I. INTRODUCTION

During last decades colliders provide most of our knowledge on fundamental constituents of matter and their interactions. Particle colliders can be classified concerning center-of-mass energy, colliding beams and collider types:

- Center-of-mass energy: energy frontiers and particle factories,
- Colliding beams: hadron, lepton and lepton-hadron colliders,
- Collider types: ring-ring, linac-linac and linac-ring.

The ring-ring colliders are most advanced from technology viewpoint and are widely used around the world. As for the linac-linac colliders, essential experience is handled due to SLC operation and ILC/CLIC related studies. The linac-ring colliders are less familiar (for history of linac-ring type proposals see [1]).

In Table I we present correlations between colliding beams and collider types for energy frontier colliders. Concerning the center-of-mass energy: hadron colliders provide highest values (for this reason they are considered as "discovery" machines), while lepton colliders have an order smaller E_{CM} (for this reason they are considered as "precision" machines), and lepton-hadron colliders provide intermediate E_{CM} . It should be mentioned that differences in center-of-mass energies become fewer at partonic level. From the BSM search point of view, lepton-hadron colliders are comparable with hadron colliders for a lot of new phenomena (for "finger estimations" see [2, 3]).

Table I: Energy frontier colliders: colliding beams vs collider types

Colliders	Ring-Ring	Linac-Linac	Linac-Ring
Hadron	+		
Lepton (e^-e^+)		+	
Lepton ($\mu^-\mu^+$)	+		
Lepton-hadron (eh)			+
Lepton-hadron (μh)	+		
Photon-hadron			+

Below we list past and future energy frontier colliders for three time periods:

- Before the LHC (<2010): Tevatron , SLC/LEP (e^-e^+) and HERA (ep),
- LHC era (2010-2030): LHC (pp , AA), ILC (e^-e^+), low energy MC ($\mu^-\mu^+$), LHeC (ep , eA) and μ -LHC (μp , μA),
- After the LHC (>2030): FCC (pp , AA), CLIC/LSC (e^-e^+), PWFA-LC (e^-e^+), high energy MC ($\mu^-\mu^+$), and FCC based lepton-hadron colliders, namely, e -FCC (ep , eA) and μ -FCC (μp , μA).

FCC is future 100 TeV center-of-mass energy pp collider proposed at CERN and supported by European Union within the Horizon 2020 Framework Programme for Research and Innovation. Main parameters of the FCC pp option [4] are presented in Table II. It includes also an electron-positron collider option at the same tunnel (TLEP), as well as several ep collider options. Construction of the FCC based ep and μp colliders will give opportunity to utilize high(est) energy of proton beam for lepton-hadron collisions.

Table II: Main parameters of the FCC pp option.

Beam Energy (TeV)	50
Peak Luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	5
Particle per Bunch (10^{10})	10
Transverse Emittance (rms, nm)	2.2
β^* amplitude function at IP (cm)	110-30
IP beam size (μm)	6.8
Bunches per Beam	10600
Time between collisions (μs)	0.025
Bunch Spacing (ns)	25
Bunch Length (rms, mm)	80
Beam-beam Tune Shift per crossing (10^{-3})	5-15

The scope of paper is following. In Section 2 we consider different options for the FCC based ep colliders and present luminosity estimations for them. Main parameters of the FCC based μp colliders are considered in Section 3. Finally, Section 4 contains summary of obtained results and recommendations.

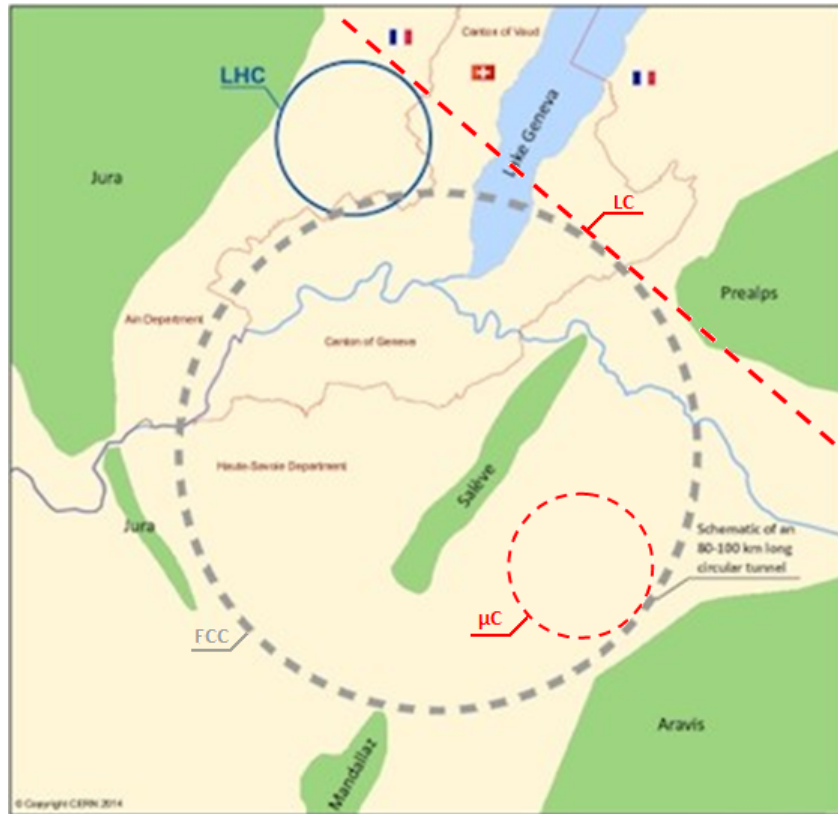


Figure 1: Possible configuration for FCC, linear collider (LC) and muon collider (μC).

II. FCC BASED ep COLLIDERS

As mentioned above FCC itself includes also e^-e^+ (TLEP) and ep collider options with $E_e = 80, 120$ and 175 GeV (W-pair threshold, Higgs and t-pair threshold, respectively). In addition the use of $E_e = 60 \text{ GeV}$ conventional energy recovery linac (ERL60), adopted as basic option for LHeC [5], for the FCC based ep collider is under consideration. One pass linac options (OPL) for the FCC based ep collider (see Fig 1), including versions with second (decelerating) linac shoulder for energy recovery (OPERL), have been considered in [6]. In Table III we present main parameters for the FCC based ep colliders. Here we add also hypothetical Linear Super Collider (see [7, 8] and references therein) and as an

extreme e-FCC case. For linac-ring type ep colliders, keeping in mind that at collision point e-beam transverse size is smaller than p-beam transverse size, expression for luminosity can be written as [9]:

$$L_{ep} = \frac{1}{4\pi} \frac{P_e}{E_e} \frac{n_p}{\varepsilon_p^N} \frac{\gamma_p}{\beta_p^*} \quad (1)$$

for round, transversely matched beams. Here E_e and P_e denote energy and beam power of electrons, respectively; $\gamma_p = E_p/m_p = 5.33 \times 10^4$ (for rest of symbols see Table 2).

Table III: Main parameters of the FCC based ep colliders

Collider name	E_e , TeV	\sqrt{s} , TeV	$L_{ep} = 10^{31} cm^{-2} s^{-1}$	L_{int}, fb^{-1} (per year)
ERL60-FCC	0.06	3.46	1000 [10]	100
FCC-e80	0.08	4.00	2300 [10]	230
FCC-e120	0.12	4.90	1200 [10]	120
FCC-e175	0.175	5.92	400	40
OPL500-FCC	0.5	10.0	8	$0.8 \rightarrow 80$
OPERL500-FCC	0.5	10.0	20000	$2000 \rightarrow 200$
OPL1000-FCC	1	14.1	4 [6]	$0.4 \rightarrow 40$
OPERL1000-FCC	1	14.1	10000 [6]	$1000 \rightarrow 100$
OPL5000-FCC	5	31.6	0.8	$0.08 \rightarrow 8$
OPERL5000-FCC	5	31.6	2000	$200 \rightarrow 20$

Luminosity values given in Table III assume simultaneous operation with pp collider. For OPL options these values can be increased using dedicated proton beams with larger bunch population [8] (this opportunity is not efficient for e-ring and ERL options due to beam-beam tune shift and disruption limitations, respectively).

The lower limit on β_p^* , which is given by proton bunch length, can be overcome by applying a “dynamic” focusing scheme [11], where the proton bunch waist travels with electron bunch during collision. In this scheme β_p^* is limited, in principle, by the electron bunch length, which is two orders magnitude smaller. More conservatively, an upgrade of the luminosity by a factor of 3-4 may be possible.

An additional order of magnitude can be handled using cooling system counteracting IBS of proton bunches [12]. Combination of three methods may give opportunity to handle two

orders higher luminosity values for all OPL options given in Table 3 (see last column).

Let us finish this section by following remark on OPERL version (Section 7.1.5 in [5]): three orders of luminosity gain assumes overoptimistic 99.9% energy recovery. For this reason we decrease values given in last column of Table 3 by an order of magnitude.

III. FCC BASED μp COLLIDERS

Muon-proton colliders were proposed almost 2 decades ago. Construction of additional proton ring in $\sqrt{s} = 4$ TeV muon collider tunnel was suggested in [13] in order to handle μp collider with the same center-of-mass energy. However, luminosity value, namely $L_{\mu p} = 3 \times 10^{35} \text{cm}^{-2} \text{s}^{-1}$, was extremely over estimated, realistic value for this option is three orders smaller [8]. Then, construction of additional 200 GeV energy muon ring in the Tevatron ring in order to handle $\sqrt{s} = 0.9$ TeV μp collider with $L_{\mu p} = 10^{32} \text{cm}^{-2} \text{s}^{-1}$ was considered in [14].

In this paper we consider another design, namely, construction of muon ring close to FCC (see Fig 1). For numerical calculation a basic expression for the luminosity [15]

$$L = f_{coll} \frac{n_1 n_2}{4\pi \sigma_x \sigma_y} \quad (2)$$

has been used. For round beams this equation transforms to

$$L_{pp} = f_{pp} \frac{n_p^2}{4\pi \sigma_p^2} \quad (3)$$

$$L_{\mu\mu} = f_{\mu\mu} \frac{n_\mu^2}{4\pi \sigma_\mu^2} \quad (4)$$

for FCC and MC, respectively. Concerning muon-proton collisions one should use larger transverse beam sizes and smaller collision frequency values. Keeping in mind that $f_{\mu\mu}$ is an orders smaller than f_{pp} , following correlation between μp and $\mu\mu$ luminosities take place:

$$L_{\mu p} = \left(\frac{n_p}{n_\mu}\right) \left(\frac{\sigma_\mu}{\max[\sigma_p, \sigma_\mu]}\right)^2 L_{\mu\mu} \quad (5)$$

Using parameters of $\mu\mu$ colliders given in Table IV [16], according to Eq. (5) we obtain parameters of the FCC based μp colliders presented in Table V.

Table IV: Muon collider parameters [16]

\sqrt{s} , TeV	0.126	0.35	1.5	3.0	6.0
Avg. Luminosity, $10^{34}cm^{-2}s^{-1}$	0.008	0.6	1.25	4.4	12
Circumference, km	0.3	0.7	2.5	4.5	6
Repetition Rate, Hz	15	15	15	12	6
β^* , cm	1.7	0.5	1	0.5	2.5
No. muons/bunch, 10^{12}	4	3	2	2	2
No. bunches/beam	1	1	1	1	1
Norm. Trans. Emittance, $\pi mm-rad$	0.2	0.05	0.025	0.025	0.025

Table V: Main parameters of the FCC based μp colliders

Collider name	E_μ , TeV	\sqrt{s} , TeV	$L_{\mu p} = 10^{31}cm^{-2}s^{-1}$	L_{int} , fb^{-1} (per year)
$\mu 63$ -FCC	0.063	3.50	0.2	0.02
$\mu 175$ -FCC	0.175	5.92	20	2
$\mu 750$ -FCC	0.75	12.2	50	5
$\mu 1500$ -FCC	1.5	17.3	50	5
$\mu 3000$ -FCC	3	24.5	300	30

Luminosity values presented in Table V assume simultaneous operation with pp collider. These values can be increased by an order using dedicated proton beams with larger bunch population [8].

IV. ep COLLIDERS BASED ON THE FCC AND PWFA-LC

Recently, multi-TeV CM energy e^-e^+ colliders based on Plasma Wake-Field Acceleration Linear Collider (PWFA-LC) have been proposed [17]. In this section we estimate parameters of ep collisions based on the FCC proton beam and PWFA-LC electron beam. For numerical calculations we use parameters presented in Tables II and VI.

The expression for luminosity of ep collisions is given by

$$L = \frac{N_e N_p}{4\pi\sigma_p^2} f_c \quad (6)$$

where σ_p is IP proton beam size, N_e and N_p are electron and proton bunch population, f_c is collision frequency. We use σ_p in Eq. (6) because electron beam size at IP is much smaller. f_c is determined by repetition rate of electron beam.

Beam-beam tune shift for proton beam is given by

$$\Delta Q_p = \frac{N_e r_p \beta_p^*}{2\pi \gamma_p \sigma_{xe} (\sigma_{xe} + \sigma_{ye})} f_c \quad (7)$$

where r_p is classical radius of proton, β_p^* is beta function of proton beam at interaction point, γ_p is the Lorentz factor of proton beam, σ_{xe} and σ_{ye} are horizontal and vertical beam sizes of electron, respectively.

Disruption parameter for electron beam is given by

$$D = \frac{2N_p r_e \sigma_{zp}}{\gamma_e \sigma_{xp} (\sigma_{xp} + \sigma_{yp})} f_c \quad (8)$$

where r_e is classical radius of electron, γ_e is the Lorentz factor of electron beam, σ_{xp} , σ_{yp} and σ_{zp} are horizontal and vertical beam sizes of proton and bunch length of proton beam, respectively. In numerical calculations we used matched electron and proton beams, namely $\sigma_{xe} = \sigma_{ye} = \sigma_p$.

Main parameters of the PWFA-LC and FCC based ep colliders are given in Table VII, where upgraded FCC means $N_p = 2.2 \times 10^{11}$, $\beta_p^* = 0.1$ m and $\sigma_p = 2.05 \mu m$. In last two columns we present N_p and L_{ep} values for limiting case $D_e = 25$.

Table VI: PWFA-LC electron beam parameters.

Beam Energy (GeV)	125	250	500	1500	5000
Peak Luminosity ($10^{34} \text{ cm}^{-2}\text{s}^{-1}$)	0.94	1.25	1.88	3.76	6.27
Particle per Bunch (10^{10})	1	1	1	1	1
Norm. Horizontal Emittance (m)	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}	1.00×10^{-5}
Norm. Vertical Emittance (m)	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}	3.50×10^{-8}
Horizontal beam size at IP (m)	6.71×10^{-7}	4.74×10^{-7}	3.36×10^{-7}	1.94×10^{-7}	1.06×10^{-7}
Vertical beam size at IP (m)	3.78×10^{-9}	2.67×10^{-9}	1.89×10^{-9}	1.09×10^{-9}	5.98×10^{-10}
Bunches per Beam	1	1	1	1	1
Repetition Rate (Hz)	30000	20000	15000	10000	5000
Beam Power at IP (MW)	6	8	12	24	40
Bunch Spacing (ns)	3.33×10^4	5.00×10^4	6.67×10^4	1.00×10^5	2.00×10^5
Bunch Length at IP (m)	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}	2.00×10^{-5}
Disruption	8.44×10^{-1}	2.39×10^{-1}	6.71×10^{-1}	3.51	21.4

Table VII: PWFA-LC-FCC parameters.

		Nominal FCC		Upgraded FCC		$D_e = 25$	
E_e (GeV)	\sqrt{s} (TeV)	L, $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$	D	L, $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$	D	$N_p(10^{11})$	L, $10^{30} \text{ cm}^{-2} \text{ s}^{-1}$
125	5.00	5.16	1.99	124	47.6	1.1	62
250	7.08	3.44	1.00	82.6	24	2.2	82.6
500	10.0	2.58	0.50	61.9	12	4.4	124
1500	17.3	1.72	0.17	41.3	4.1	12	240
5000	31.6	0.86	0.05	20.8	1.2	44	400

One can see from Table III that luminosity of ep collisions of order of $10^{32} \text{ cm}^{-2} \text{ s}^{-1}$ is achievable for all PWFA-LC stages. In principle luminosity values may be increasing by an order using dynamic focusing for proton beams [11, 12].

V. CONCLUSION

The FCC based ep and μp colliders will provide opportunity to achieve multi-TeV center-of-mass energy scale at partonic level in lepton-hadron collisions with sufficiently high luminosities. Summary of main parameters of these machine, which can be used by our colleagues for research of physics search potential of e-FCC and μ -FCC, is given in Table VI. As an example, FCC based ep (μp) colliders have a great potential for the first (second) family leptoquarks and color octet electron (muon) search. There are a lot of BSM phenomena which can be investigated in the best manner at multi-TeV scale lepton-hadron colliders. Finger estimations show that BSM physics search potential of ep colliders is comparable to that of FCC and essentially exceeds that of corresponding e^+e^- collider (for comparison of the LHC pp, ILC e^+e^- and ILC-LHC ep search potentials see [3] and references therein). Moreover, these machines will provide opportunity to investigate extremely small x-Bjorken region, which is crucial for clarifying the QCD basics, as well as the origin of 98% of mass of visible universe [18].

Table VIII: Summary of main parameters of the FCC based lp colliders

Collider name	E_l, TeV	\sqrt{s}, TeV	$L_{int}, fb^{-1}(\text{per year})$
ERL60-FCC	0.06	3.46	100
FCC-e80	0.08	4.00	230
FCC-e120	0.12	4.90	120
FCC-e175	0.175	5.92	40
OPL500-FCC	0.5	10.0	10-100
OPERL500-FCC	0.5	10.0	100-300
OPL1000-FCC	1	14.1	5-50
OPERL1000-FCC	1	14.1	50-150
OPL5000-FCC	5	31.6	1-10
OPERL5000-FCC	5	31.6	10-30
$\mu 63$ -FCC	0.063	3.50	0.1-1
$\mu 175$ -FCC	0.175	5.92	2-20
$\mu 750$ -FCC	0.75	12.2	5-50
$\mu 1500$ -FCC	1.5	17.3	5-50
$\mu 3000$ -FCC	3	24.5	10-100
PWFA125-FCC	0.125	5	1-10
PWFA250-FCC	0.25	7.08	1-10
PWFA500-FCC	0.5	10.0	1-10
PWFA1500-FCC	1.5	17.3	2-20
PWFA5000-FCC	5	31.6	4-40

It should be noted that OPL/OPERL-FCC and PWFA-LC-FCC ep colliders will give opportunity to construct also γp colliders with approximately same center-of-mass energy and luminosity. In addition approval of the FCC AA collider option will give opportunity to handle also multi-TeV energy γA and μA collisions (see review [8] and references therein). Also FEL γA option has a great potential for nuclear spectroscopy. These options are under consideration [19].

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- [1] A. Akay, H. Karadeniz and S. Sultansoy, "Review of linac-ring-type collider proposals", Int. J. Mod. Phys. A 25 (2010) 4589.
- [2] U. Amaldi, "Physics and detectors at the Large Hadron Collider and at the CERN Linear Collider", Workshop on Physics at Future Accelerators, CERN Yellow report 87-07, p. 323 (1987).
- [3] S. Sultansoy, "A review of TeV scale lepton-hadron and photon-hadron colliders", Proc. of 2005 Particle Accelerator Conference, p. 4329 (2005).
- [4] FCC pp option parameters, <https://fcc.web.cern.ch/Pages/Hadron-Collider.asp>.
- [5] J. L. Abelleira Fernandez et al. (LHeC Study Group), "A Large Hadron Electron Collider at CERN: Report on the Physics and Design Concepts for Machine and Detector", J. Phys. G: Nucl. Part. Phys. 39 (2012), 075001.
- [6] U. Kaya, M. Sahin, S. Sultansoy, "Majorana Neutrino and WR at TeV scale ep Colliders", (2015), arXiv:1502.04115v2[hep-ph].
- [7] S. F. Sultanov, "Prospects of the future ep and γp colliders: luminosity and physics", ICTP preprint, IC/89/409 (1989).
- [8] S. Sultansoy, "The post-HERA era: brief review of future lepton-hadron and photon-hadron colliders", DESY 99-159, AU-HEP-99/02; arXiv:hep-ph/9911417v2.
- [9] M. Tigner, B. Wiik and F. Willeke, "An Electron-Proton Collider in the TeV Range", Proc. of 1991 Particle Accelerator Conference, p. 2910 (1991).
- [10] F. Zimmermann, "Challenges for Highest Energy Circular Colliders", KEK Accelerator Seminar, 31 July 2014, Tsukuba, Japan.
- [11] R. Brinkmann and M. Dohlus, "A method to overcome the bunch length limitations on β_p^* for electron-proton colliders", DESY-M-95-11 (1995).
- [12] R. Brinkmann, "Interaction Region and Luminosity Limitations for the TESLA/HERA e/p Collider", Turk J. Phys, 22 (1998) 661.

- [13] I. F. Ginzburg, "Physics at future ep , γp (linac-ring) and μp colliders", Turk J. Phys, 22 (1998) 607.
- [14] V. D. Shiltsev, "An asymmetric muon proton collider: luminosity consideration", Proc. of 1997 Particle Accelerator Conference, p. 420 (1988).
- [15] J. Beringer et al. (Particle Data Group), Phys. Rev. D 86, 010001 (2012).
- [16] J. P. Delahaye et al., "A staged muon accelerator facility for neutrino and collider physics", Proc. of 2014 International Particle Accelerator Conference, p. 1872 (2015).
- [17] J-P. Delahaye et al. , "A Beam Driven Plasma-wakefield Linear Collider from Higgs Factory to Multi-TeV", Proceedings of IPAC 2014, page 3791.
- [18] S. A. Cetin, S. Sultansoy and G. Unel, "Why QCD Explorer stage of the LHeC should have high(est) priority", arXiv:1305.5572 [physics.acc-ph].
- [19] Y. C. Acar, U. Kaya, B. B. Oner and S. Sultansoy, "FCC based lepton-hadron and photon-hadron colliders", in preparation.